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DEVELOPMENT OF A BRUSHLESS DC MOTOR FOR SATELLITE APPLICATION

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SUMMARY

The Goddard Space Flight Center, is sponsoring a development program which has developed a brushless motor with true dc motor characteristics. Photo-optical detectors and transistorized switching duplicate the functions of the conventional commutator without physical contact. The 3-watt prototype motors have a starting torque of 2.7 oz-in and achieve fifty percent efficiency (.67 oz-in) at 3000 rpm, the speed chosen to reduce bearing and gearing problems anticipated in operation in outer space.

The motor performance compares favorably with conventional dc motors and should significantly improve the efficiency of present systems employing ac motors and inverters. An exceptionally fast response time ($< .010$ sec) and control at the milliwatt power level will be of value in servo applications. High starting torque and system efficiency recommend the motor for consideration whenever a source of mechanical power is required and brush life or arcing have previously ruled the dc motor out of consideration.

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(Manuscript received July 18, 1963)

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INTRODUCTION

The Goddard Space Flight Center is sponsoring a program which has developed a "brushless" motor (Figure 1) of true dc motor characteristics. This motor designed specifically for spacecraft operation, promises to significantly increase the efficiency of power conversion from electrical to mechanical energy. The motor has other assets which further tend to make it a very attractive component for a wide variety of applications, such as servo mechanisms, tape recorder drives, reaction wheels, etc.

HISTORICAL REVIEW

One of the basic mechanical problems is motion. The most effective and versatile type of motion is provided by rotating machinery. Since the readily available and storable form of energy aboard spacecraft is electrical, motors are a key element in all but the most elementary form of spacecraft.

Motors, in general, are chosen according to the type of electrical power available—either ac or dc. Spacecraft power sources are almost universally dc because of the nature of the devices—i.e., solar cells, thermoelectric converters—and because electrical energy is storable in this form. Hence, dc motors should be ideally suited for spacecraft use. But, the barrier to the use of dc motors in space has been the problem of brush life in a vacuum environment.

Another reason for preferring dc motors is their high efficiency. Electrical power is

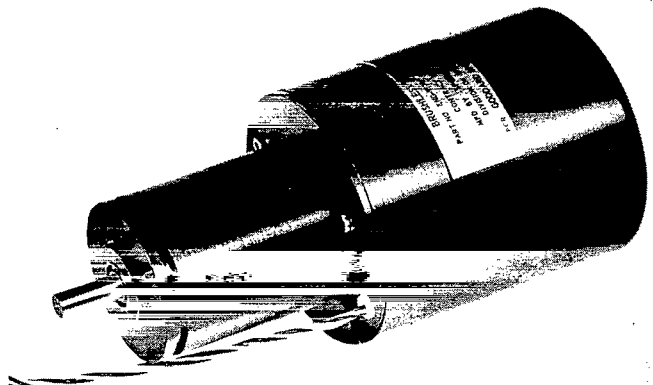


Figure 1—The Prototype Motor.

valuable; and, at the present time, energy collection, storage, and the associated conversion, regulation, and appendages represent between 20 and 40 percent of the total weight of satellites now on the drawing boards and under construction. The higher figure is generally related to smaller types and the smaller percentage to larger, oriented devices. These systems have weights ranging between $3/4$ and $1-3/4$ pounds per watt and these figures do not include the fact that significant portions of the structural and control devices are required specifically for the paddles, battery support members, etc. Any savings that can be made in reducing power conversion losses represent sizable decreases in the overall payload weight and booster requirements. Conversely, with a given amount of available power, a satellite's capabilities can be increased dramatically if the power needed to perform a given function is reduced.

With these facts in mind, the number one problem heretofore plaguing the use of dc motors in space was attacked in early 1962. This was that brush life of conventional carbon brush commutators was measured in minutes when operated in a vacuum environment. Development of electronic commutators in the industry was rumored, but a preliminary search found none commercially available.

DEVELOPMENTAL PROGRAM

Proposals were solicited from the industry for the development and prototype manufacture of a brushless motor with true dc motor characteristics. A contract was awarded to Sperry Farragut Company whose proposal indicated a firm groundwork had been laid. Basic to the problem were two functions:

1. Detecting the position of the rotor and,
2. Driving switches of sufficient power handling capability from a relatively weak detected signal.

The contractor's approach had been to use light sensitive photodiodes and a rotating shutter to determine the rotor position, and transistorized amplification and power switching to commutate (or direct) the input power.

The principle of operation of this motor is identical to the conventional dc motor (see Figure 2). A torque is produced when two magnetic fields are established with a relative angle between them. This torque reaches a maximum when the relative angle is ninety degrees. It is the function of the commutator to apply the external power to the motor windings in such a manner as to maintain this angle for all positions of the rotating member.

This motor is inverted in comparison to a conventional dc motor, in that the rotor is a permanent magnet and the stator is wound, as may be noted in Figure 3. Attached to the rotor is a light shield which serves to direct the light beam of the stationary lamp to a particular photo-diode as it rotates. When illuminated, the photo-diode conducts a current which is amplified and directed to the bases of a pair of switching transistors. These apply the power supply voltage to the proper points on the ring type stator winding. There are six identical sets of photo-diodes and transistor switches, each turned on in sequence for 60° /revolution. Thus, this commutation action is

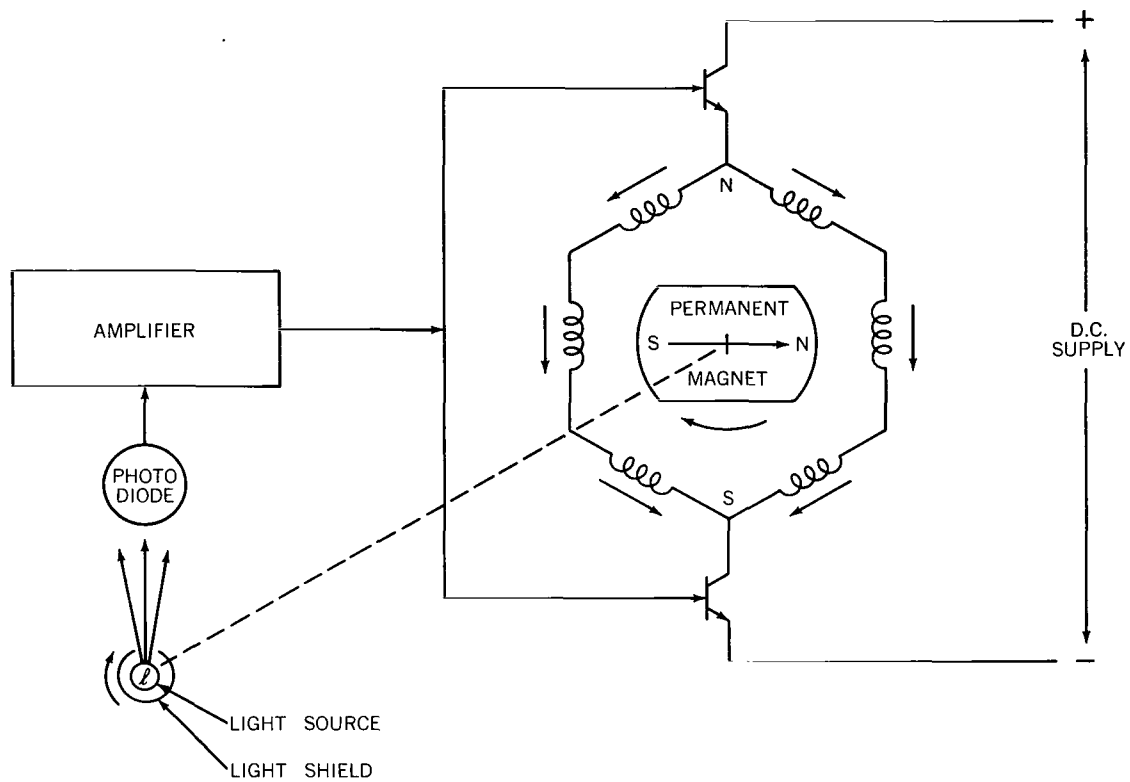


Figure 2—Schematic diagram of the motor.

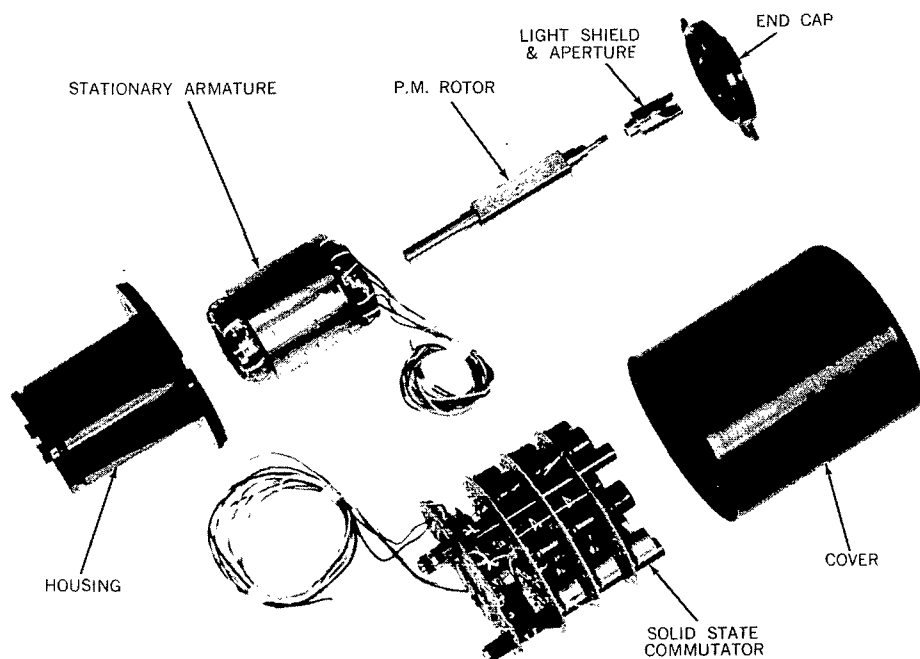


Figure 3—The motor parts.

identical to that provided by the conventional carbon brush and segmented copper ring, but performed without physical contact of moving parts.

In the course of this development, several alternate methods were investigated as new solid state devices became commercially available (high-impedance thin-film Hall-effect devices, magnetosensitive resistors, and photosensitive silicon controlled rectifiers). Hall-effect devices have the distinct advantage of being bilateral devices, capable of both positive and negative outputs, thereby reducing by one-half the number of detectors required. They are also solid state devices with no wear-out mechanism inherent in their operation. The disadvantages, shared by the magnetoresistive elements, include the distributed area of sensitivity, the relatively broad slope of the flux change possible, and the weight of the magnetic assembly required. The photo-sensitive silicon controlled rectifiers are, at first glance, capable of yielding the ultimate in simplicity due to their ability of combining the detecting and switching functions into one unit. Problems associated with their application hinge on the turn-off circuitry and the fact that a light source was still required.

While none of these approaches presented insoluble problems, the experimental evidence continued to favor the photo-optical transistorized commutator. Several developments prompted a decision to continue in this direction; among them were the rather surprisingly good preliminary results of light source environmental tests, and a circuitry of demonstrated capability, light and small enough to satisfy the packaging goals for prototype hardware. Low voltage tungsten filament lamps survived vibration levels of 50 g's and shocks of 130 g's on a hard mount.

In spite of the fact that supplier delays prevented experimenting with some of the newer magnetic alloys; the motor design meets the original goal of 50 percent efficiency, the system's outstanding attribute. Coupled with this is the fact that this design, due to the small rotor dimensions (3/8" diameter), exhibits an exceptional torque to inertia ratio, giving it superior servo motor characteristics.

THE PROTOTYPE MOTOR

The specific motor design as developed under the present contract has the following performance specifications (Figure 4):

Power Input	3 watts at 24 v dc
Torque	.67 oz-in at 3000 rpm
Torque, Stall	2.7 oz-in at 10.2 watts
No Load Speed	3900 rpm

Although this motor was designed for a specific set of conditions, the design concepts are versatile and, in fact, higher efficiencies have been obtained at higher operating speeds. Motor size, power, and speed can be scaled up or down with a fair degree of confidence.

The commutator utilizes a miniature tungsten lamp which is derated to give a theoretical filament life of one million hours. It produces an output of three thousandths candlepower while using

.3 watt. The detecting device is a silicon photo device with a rise time of 1.5 micro-seconds and a fall time of 15 micro-seconds. Consequently, it is capable of far higher speeds than are presently being employed. The power switches are silicon power transistors rated to 3 amperes with a leakage current well under 1 milliamp at 150°C.

The motor design employs a minimum diameter Alnico V rotor capable of handling a reasonable air gap clearance. The length of the motor was chosen to minimize the power loss in the "end turns." A high silicon steel was utilized for the stator on the basis of high saturation flux density. The stator is laminated to reduce core losses and the slots skewed to minimize cogging. Ball bearings, the only moving parts in physical contact, are preloaded to reduce runout of the titanium shaft. Heavy polyvinyl acetal insulation was specified for the motor windings.

At the design speed of 3000 rpm, ten percent of the power is used by the lamp and only six percent in the electronics—more than half of which is dissipated in the isolation resistors and not in the active devices. Winding resistance accounts for twenty-two percent and "speed" losses, which include bearings, air friction, and core losses in the iron, the remaining thirteen percent. Mechanical power available at the shaft is one-half the input power.

COMPARISON WITH OTHER SYSTEMS

The gap that this motor fills is best illustrated by looking over a list of typical commercially available devices, just as a design engineer might do when looking for a device to meet a specific satellite requirement (Table 1).

Take a case, for purpose of illustration, that a shaft must turn at 30 rpm with a 40 ± 20 percent oz-in load on a semicontinuous basis.

The ordinary dc motors with their tempting power efficiencies, must be bypassed due to the problem of brush life. Also bypassed is the stepper motor due to its very low efficiency.

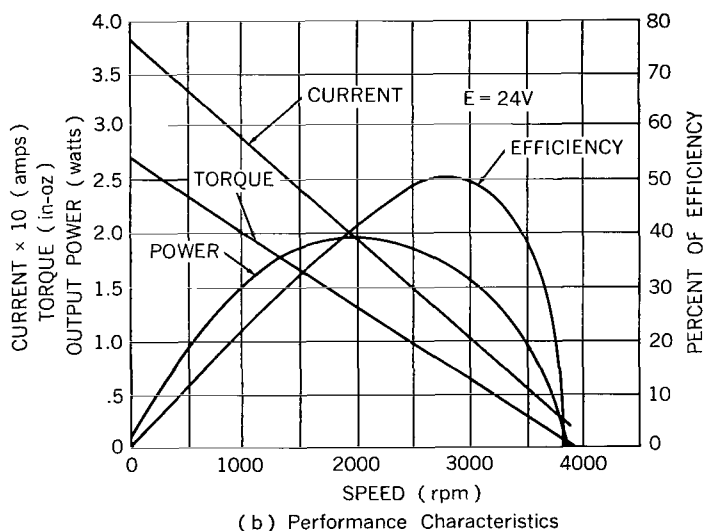
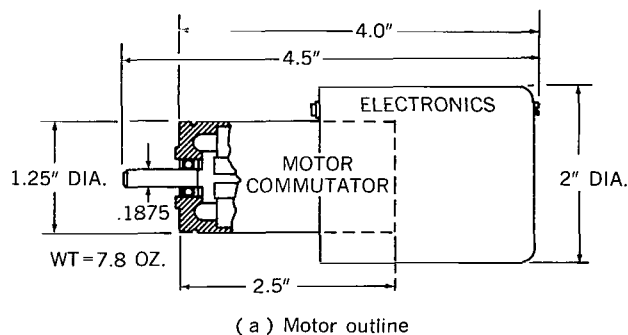


Figure 4—Performance curves.

Table 1

Typical Characteristics of 9 Types of Motors

Type	Torque at Rated Speed (oz-in)	Efficiency Percent at Rated Speed	Speed (rpm)	Power Input (watts)	Current (volts)	Torque Stall (oz-in)	Diameter (inches)	Length (inches)
GSFC-NASA Brushless D.C.	.67	50	3,000	3	24 dc	2.7	2.0	4.0
Brushless Induction	1.5	36	30,000	100	28 dc	1.5	1.5	
Brushless Induction	.8	22	5,100	14	28 dc	.4	3.0	2.5
A.C. Induction	2.5	55	10,400	36	115 dc	1.0	1.5	2.25
A.C. Hysteresis	.75	17	3,600	12	115 ac	.75	1.2	2.6
Perm. Mag. Servo	.35	5	725	4	115 ac	.73	1.1	1.5
Stepper	.20	1	200	3.8	27 dc (Chopped)	.20		
D.C. Servo	.21	34	13,500	7	28 dc		.8	1.0
D.C. Servo	19.0	44	3,500	96	12 dc	60.0	4.0	2.0
D.C. Motor	.7	53	17,000	23	27 dc	4.6	1.0	1.7
D.C. Motor	1.8	63	15,000	32	26 dc	9.7	1.25	2.5
D.C. Torquer	NA	--	Zero	3	28 dc	5.8	1.9	.5

The permanent magnet induction servo merits some consideration due to its low speed characteristic:

$$\frac{725 \text{ rpm}}{30 \text{ rpm}} \times .35 \text{ oz-in} = 8.5 \text{ oz-in (insufficient torque).}$$

The hysteresis motor looks somewhat better:

$$\frac{3600 \text{ rpm}}{30 \text{ rpm}} \times .75 \text{ oz-in} = 90 \text{ oz-in}$$

$$(120:1 \text{ reduction}) \times .75 \text{ gear train efficiency.}$$

$$\text{Output} = 67.5 \text{ oz-in}$$

The 12 watt ac power requirement is rather large and with 20 percent losses anticipated in the inverter; this would require 15 watts dc battery power.

Induction motors are more efficient:

$$\frac{10,400 \text{ rpm}}{30 \text{ rpm}} \times 2.5 \text{ oz-in} = 870 \text{ oz-in}$$

$$(346:1 \text{ reduction}) \times .70 \text{ gear train efficiency,} \\ \text{Output} = 610 \text{ oz-in}$$

which is an order of magnitude higher than necessary. However, a similar motor should be available with one-tenth this output and perhaps using one-tenth the power, or 3.6 watts ac. This would be acceptable even though inverter losses would increase the battery supply requirement to 4.5 watts dc. This is still not a good solution on two counts, bearing and gear life are seriously degraded at these speeds, and starting torque is too low (0.42 oz-in)

Now investigating a brushless inductive motor, we see that

$$\frac{5,100 \text{ rpm}}{30 \text{ rpm}} \times .8 \text{ oz-in} = 136 \text{ oz-in;}$$

$$(170:1 \text{ reduction}) \times .70 \text{ gear train efficiency.} \\ \text{Output} = 96 \text{ oz-in}$$

Again 14 watts dc power is high.

Another motor of the same type would cut this to 8.5 watts but only by operating at a speed which is out of the question.

Consider this brushless dc motor:

$$\frac{3000 \text{ rpm}}{30 \text{ rpm}} \times .67 \text{ oz-in} = 67 \text{ oz-in;}$$

$$(100:1 \text{ ratio}) \times .75 \text{ gear train efficiency;} \\ \text{Output} = 50 \text{ oz-in}$$

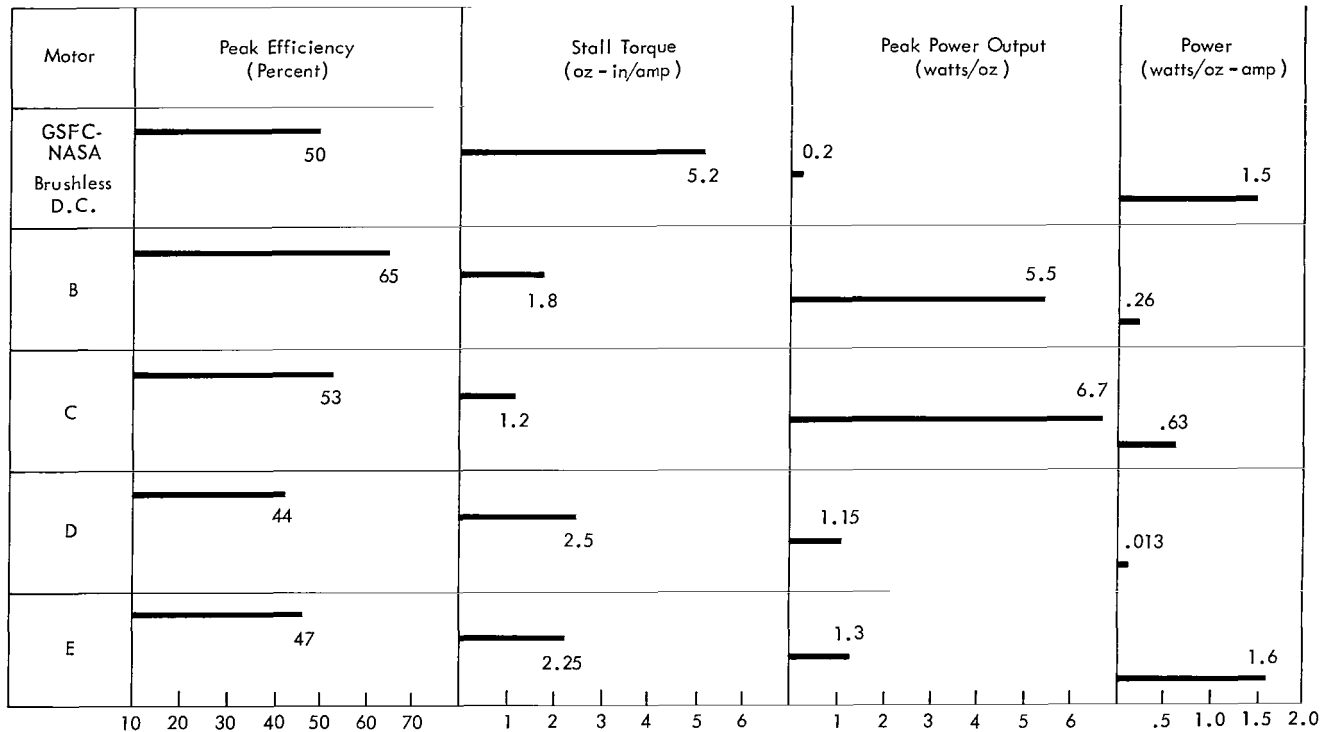
$$\text{Power} = 3 \text{ watts;}$$

$$\text{Starting Torque } 240 \text{ oz-in} \times .75 = 180 \text{ oz-in.}$$

The relatively low speed (3,000 rpm) alleviates the bearing and gearing problems and requires a smaller gear reducer. No additional weight or power loss is involved since it operates directly off the dc battery supply without an inverter.

Another worthwhile comparison is to see where this motor stands with respect to conventional permanent magnet dc motors. By referring to Table 2 it can be seen that its efficiency is comparable to some good quality motors but 15 percent under the best. Stall torque per ampere exceeds the

Table 2
Characteristics of Several dc Motors



conventional motor by a factor of two. In the category of peak power output per ounce, a large variation is found, with this motor an order of magnitude below a typical motor. This is the result of the effort to design for a low power input capability and the low speed operation desired. But, when this value is divided by the current used, the figures in the next column are obtained, and where weight and power are both limited, as in spacecraft, this motor again appears at the top of the list. It should be remembered that these latter comparisons are made to motors not suitable for spacecraft operation due to the brush life problem.

Early in the test program the fast response exhibited by the motor was noted. This led to a comparison with typical servo motor characteristics and it was found that it could easily meet SAE and BuOrd specifications for a Size 18 servo even though the motor frame is only a Size 12.. They are compared in Table 3.

It is felt that this motor concept may well stimulate great interest in the servomechanism field because, in addition to the excellent response time, it is controllable at a milliwatt power level. This is due to the nature of the electronic commutator which has self contained power amplification.

Numerous brushless motor developments have been published recently. Not all of these have the dc motor characteristics of high starting torque and high efficiency. This motor has a linear torque-current relationship with maximum torque developed at stall.

Table 3

Comparison of this Motor and a BuOrd Servo

Quality	GSFC-NASA	A BuOrd Quality ac Servo
Starting Torque	2.7 oz-in	2.4 oz-in
Diameter	2.0 in	1.75 in
Weight	8.5 oz	12.2 oz
Theoretical Acc. at Stall	70,000 rad/sec ²	39,700 rad/sec ²
Input Watts at Stall	10.2 w	18.2 w
Input Watts at Speed	3.0 w	13.6 w
Servo Time Constant	< .010 sec	.0131 sec

The current and (assuming a constant dc supply voltage) the power used by this type of motor is only what is required by the load. In many cases this is only 25 percent or less of the peak requirement. Consequently, the average power requirement of a system employing a motor of this type may be less than one quarter of what is used by a constant speed motor, and still have a two to one factor of safety in starting ability under load. In addition, this motor has been specifically designed for low speed operation, easing the problem of bearing and gearing life in a vacuum. At higher speeds the motor is more efficient.

Now, not all points of comparison are this favorable. In the use of ac motors some capabilities are obtained which are not normally associated with dc machines. Number one is the inherent synchronous operation, another is the relatively well developed technology in inverter design which over the years has produced a product of known capability and reliability.

RESULTS

To summarize the present status of the brushless dc motor program:

1. Four prototype motors of fine capability specifically designed for low power spacecraft applications have been designed and built;
2. Sufficient knowledge has been developed regarding the design parameters to be able to confidently design motors of similar quality for applications requiring widely different power levels.

Further, groundwork has been laid for the following development efforts:

1. Breadboard circuits have been operated demonstrating the feasibility of considerably reducing the complexity of the electronic circuitry;

2. Design calculations have been made which utilize some of the newer magnetic alloys and special winding techniques which potentially are capable of efficiencies in the range of 60 to 70 percent;
3. The possibility of obtaining synchronous speed control without losing the performance of the dc motor appears feasible; and
4. A two speed motor with two independent windings is being fabricated for a developmental meteorological satellite tape recorder.

CONCLUSIONS

It is felt that this effort is a step forward in spacecraft technology, namely in providing more efficient motive power in space. Further, it is believed that it has opened the door to new areas of worthwhile development, specifically: speed control of dc motors, simplifications yielding increased reliability and economy in the solid state commutation circuitry, and further increases in the efficiency of miniature motors.

Now that the fundamental limitation on the use of dc motors in spacecraft has been overcome, it is reasonable to expect their increasing application. The high starting torque and high system efficiency recommend it for consideration whenever a source of mechanical power is required.